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1. Introduction

1.1 Overview

Since 1990, EPA has sought to reduce greenhouse gas (GHG) emissions through a variety of partnership programs that promote the use of energy efficient technologies and management practices. Most of the focus on reduction opportunities has been on energy-related carbon dioxide (CO₂) emissions, which currently account for about 81 percent of the total U.S. GHG emissions (EPA, 2001).¹ However, reduced emissions of the non-CO₂ GHGs—methane, nitrous oxide, and the high global warming potential (GWP) gases hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride (HFCs, PFCs, and SF₆)—can also make a contribution to cost-effective GHG emission reductions (see, for example, Hayhoe *et al.*, 1999; Reilly *et al.*, 1999a and 1999b). This report has been developed, in part, to better characterize the role of the high GWP gases as part of a comprehensive GHG mitigation approach. To this end, this report develops marginal abatement cost data that can be used in macroeconomic analyses of climate change mitigation strategies.

This report has three objectives. First, it presents EPA's current forecasts of U.S. high GWP gas emissions through 2010 under a "business-as-usual" scenario that assumes no further actions are taken to reduce emissions. Second, the report uses available cost and technical data to describe those technologies and practices that can reduce these emissions from the major emission sources, some of which are expected to be voluntarily adopted by industry. Third, the report estimates the costs of reducing high GWP gas emissions for each major source and assembles these costs into a marginal abatement curve (MAC) that shows the total emission reductions achievable at increasing monetary values of carbon, for the year 2010. This introduction describes the general methodological issues for estimating the MAC.

The remainder of this report is organized into the following chapters. Each chapter corresponds to one of the major source categories of high GWP gases:

- Chapter 2. HFC-23 Emissions from HCFC-22 Production
- Chapter 3. SF₆ Emissions from Electric Power Transmission and Distribution Systems
- Chapter 4. SF₆ Emissions from Magnesium Production and Parts Casting
- Chapter 5. PFC Emissions from Aluminum Smelters
- Chapter 6. PFC, HFC, and SF₆ Emissions from Semiconductor Manufacturing
- Chapter 7. HFC Emissions from Refrigeration and Air-Conditioning
- Chapter 8. HFC and PFC/PFPE Emissions from Solvents
- Chapter 9. HFC Emissions from Foams
- Chapter 10. HFC Emissions from Aerosols
- Chapter 11. HFC and PFC Emissions from Fire Extinguishing

¹ Emissions are weighted by 100-year global warming potentials (GWPs).

Each chapter presents the following information:

- *Baseline Emissions of High GWP Gases.* The source of the emissions in the United States is summarized, followed by a baseline forecast of U.S. emissions from that source through 2010. This baseline is estimated under a “business-as-usual” case scenario and assumes that no further voluntary actions are taken to reduce emissions.
- *High GWP Gas Emission Reduction Options and Associated Costs.* Each chapter summarizes the known technologies and practices for reducing the emissions from the source and estimates a cost for reducing emissions in terms of dollars per metric ton of carbon equivalent (\$/TCE).

The framework for this analysis is national in scope, consistent with the intent to develop inputs useful for macroeconomic studies of potential climate change policy. Given this broad view, this report does not present highly detailed analyses of the individual sources of high GWP gas emissions, nor does it attempt to comprehensively evaluate the comparative advantages or technical challenges of alternative technologies in specific industry sectors. Rather, EPA has largely relied on available literature and expert review to identify possible options in the different industries that use high GWP gases to provide credible estimates of emissions and costs under alternative scenarios. Where detailed data and information have been available, as is the case for the refrigeration and air-conditioning sector, a more detailed treatment is presented. EPA intends to update this analysis over time as more information is developed.

1.2 Background

The use of hydrofluorocarbons (HFCs) has allowed the rapid phaseout of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and halons in the U.S. and other countries for applications where other alternatives were not available. HFCs have generally been selected for applications where they provide superior technical (reliability) or safety (low toxicity and flammability) performance. In many cases, HFCs provide equal or better energy efficiency compared to other available alternatives, thereby

Exhibit 1.1: Major High GWP Gases in the United States (100-year GWPs)^a

Gas	GWP	Atmospheric Lifetime (yrs)	Source of Emissions
HFC-23	11,700	264	HCFC-22 Production, Fire Extinguishing Equipment, Aerosols, Semiconductor Manufacture
HFC-43-10mee	1,300	17.1	Solvents
HFC-125	2,800	32.6	Refrigeration/Air-Conditioning
HFC-134a	1,300	14.6	Refrigeration/Air-Conditioning, Aerosols, Foams
HFC-143a	3,800	48.3	Refrigeration/Air-Conditioning
HFC-152a	140	1.5	Refrigeration/Air-Conditioning, Aerosols, Foams
HFC-227ea	2,900	36.5	Aerosols, Fire Extinguishing Equipment
HFC-236fa	6,300	209	Refrigeration/Air-Conditioning, Fire Extinguishing
SF ₆	23,900	3,200	Electric Utilities; Magnesium Production; Semiconductor Manufacture
PFCs (primarily CF ₄ and C ₂ F ₆)	6,500 – 9,200	2,600-50,000	Aluminum Smelting, Semiconductor Manufacture, Fire Extinguishing
PFC/PFPEs ^b	7,400	3,200	Solvents

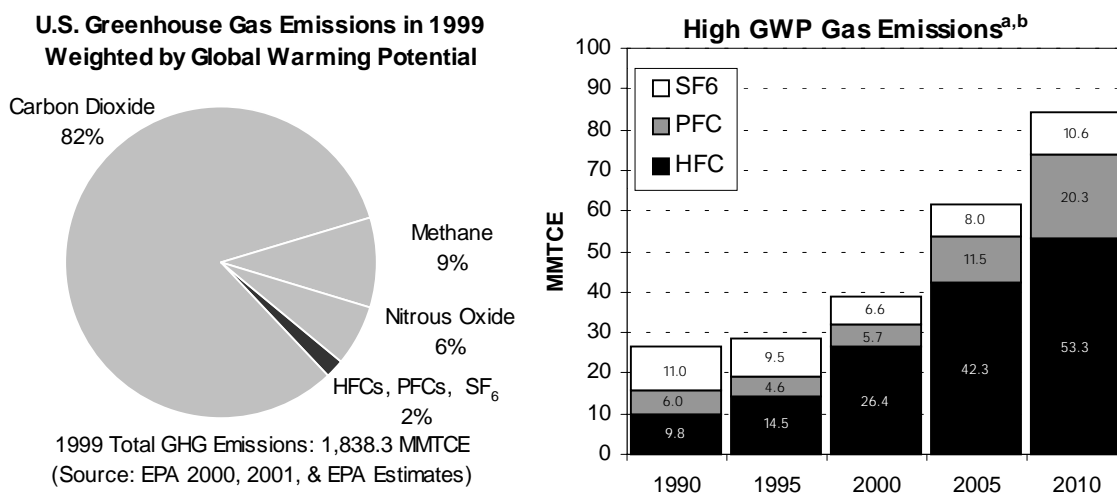
^a Note that this table lists major commercial gases and sources; other minor gases and uses such as lab applications are not listed here. The GWP and atmospheric lifetimes are taken from Climate Change 1995, the IPCC Second Assessment Report (Schimel *et al.*, 1995).

^b PFC/PFPEs are a diverse collection of PFCs and perfluoropolyethers (PFPEs) used as solvents.

reducing long-term environmental impacts. HFCs are expected to replace a significant portion of past and current demand for CFCs and HCFCs in insulating foams, refrigeration and air-conditioning, propellants used in metered dose inhalers, and other applications. HFCs are also becoming important substitutes for halons used in specialized fire protection equipment. Perfluorocarbons (PFCs) have been introduced in a small number of applications as alternatives to ozone depleting substances (ODS), specifically in very limited refrigeration and fire protection applications, and as important agents in semiconductor manufacture. However, these gases, along with SF₆, which is used as a dielectric or cover gas in industrial applications, are many times more effective (on a per ton basis) than CO₂ in trapping heat in the atmosphere. The GWPs of these gases range from 140 to over 23,900 times the global warming capability of CO₂, and in some cases these gases remain in the atmosphere for hundreds or thousands of years (see Exhibit 1.1). However, the most widely used high GWP gas is HFC-134a, which has a shorter lifetime of about 15 years.

Although these high GWP gases currently account for about two percent of the GWP-weighted U.S. greenhouse gas emissions, their use and emissions are growing (EPA, 2001). Exhibit 1.2 shows that by 2010, high GWP gas emissions could increase to over three times 1990 levels if no further reduction actions are taken. This forecast is based on a “business-as-usual” case, without taking into account industry’s voluntary efforts to reduce emissions. Because of voluntary actions underway or planned by several industry sectors, actual emission growth is expected to be smaller.

Exhibit 1.2: Contribution of High GWP Gas Emissions to U.S. Greenhouse Gas Emissions



^a A fraction of the HFCs in this exhibit may also include PFC/PFPEs. This term is a proxy used to describe a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

^b Forecast emissions (years 2000, 2005, and 2010) are based on a “business-as-usual” scenario, assuming no further action.

1.3 Historical and Baseline High GWP Gas Emissions Estimates

The methodology for estimating current and future emissions of high GWP gases varies with the source, as described below.

ODS Substitutes. EPA uses a detailed vintaging model of ODS-containing equipment and products to estimate the use and emissions of various ODS substitutes, principally HFCs and PFCs. The Vintaging Model estimates ODS and ODS substitute use in the United States based on estimates of the quantity of equipment or products sold each year containing these chemicals, and the amount of the chemical

required to make or maintain equipment and products over time. Emissions for each end use—including refrigeration and air-conditioning, solvents, foams, aerosols, and fire extinguishing—are estimated by applying annual leak rates and release profiles. The model aggregates data for more than 40 end uses, keeping track of equipment vintages to estimate annual use and emissions of each compound. Appendix A presents a detailed description of the Vintaging Model.

Other Industrial Sources. Emissions of the high GWP gases from other industrial sources—PFCs, HFCs and SF₆ from semiconductor manufacturing; PFCs from aluminum production; SF₆ from the magnesium and electric power systems sectors; and HFC-23 from HCFC-22 production—are estimated from production characteristics of the end use that emits each gas. For some production-related industrial processes, an emission factor is applied that relates the high GWP gas emissions to the output of the process (e.g., HCFC-22 production drives HFC-23 emission estimates and magnesium production determines some SF₆ emissions). For other industries, emissions are related to specific characteristics of the production process. For example, PFC emissions from transitory “anode effects” in aluminum smelting depend on the frequency and duration of the process characteristic that produces this gas. For SF₆ used as insulation in electrical transmission and distribution systems, emissions are more directly related to equipment characteristics (e.g., age and size) and sales of SF₆ than to electricity production.

Exhibit 1.3 presents the emission estimates of high GWP gases by source for the years 1990 through 1999. As the exhibit illustrates, there has been a rise in ODS substitute emissions since 1990 and steady growth in emissions from most of the remaining high GWP sources. In some cases, declines in emissions are a result of voluntary emission reduction efforts by industry undertaken through EPA partnership programs under the Climate Change Action Plan (CCAP). For example, under the Voluntary Aluminum Industrial Partnership (VAIP), emissions of PFCs from aluminum smelting have fallen by over 50 percent from 1990 levels.

Exhibit 1.3: Historical U.S. High GWP Gas Emissions (MMTCE)

Source of High GWP Gases	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
HFC-23 from HCFC-22 Production	9.5	8.4	9.5	8.7	8.6	7.4	8.5	8.2	10.9	8.3
Electric Power Systems (SF ₆)	9.5	9.9	9.2	10.4	9.5	8.0	8.1	7.4	6.1	4.7
Magnesium (SF ₆)	1.5	1.5	1.5	1.5	1.4	1.5	1.5	2.0	1.7	1.7
Aluminum (PFCs)	5.3	4.7	4.4	3.8	3.1	3.1	3.2	3.0	2.8	2.7
Semiconductors (PFCs, HFCs & SF ₆)	0.8	0.8	0.8	1.0	1.2	1.5	1.9	1.9	1.9	1.9
Total of ODS Substitutes	0.3	0.4	0.6	1.7	3.0	7.1	9.9	12.1	14.2	16.2
TOTAL	26.8	25.6	26.0	27.1	26.8	28.6	33.2	34.7	37.6	35.5

Source: EPA 2000, 2001, and EPA estimates.

Notes:

The ODS substitutes include the refrigeration and air-conditioning, solvents, foams, aerosols, and fire extinguishing industries.

Sums might not add to total due to rounding.

The baseline forecast of high GWP gas emissions for the years 2000-2010 is presented in Exhibit 1.4. Overall, the exhibit shows that emissions could be expected to grow substantially over the forecast period, primarily from the use of ODS substitutes. The introduction of ODS substitutes to the refrigeration and air-conditioning sector is the major driver of this growth, primarily because the sector is so large. The only sector where emissions decline over the forecast period is HFC-23 emissions from HCFC-22 manufacturing, because the phaseout of certain HCFC uses in the United States is expected to impact HCFC-22 demand.

These projected baseline emission estimates do not include further reductions that are expected to result from implementation of continued voluntary actions across these industries. As a result, actual future

emissions are expected to be lower than this analytical baseline. Because these programs are voluntary, industry decisions to pursue reductions will depend on the cost-effectiveness of the reduction options. A major purpose of this report is to estimate the cost-effectiveness of various emission reduction options and to determine the quantity of future emission reductions achievable at different values of carbon.

Exhibit 1.4: Baseline U.S. High GWP Gas Emissions (MMTCE)

Sources of High GWP Gases	Forecast Emissions		
	2000	2005	2010
HFC-23 from HCFC-22 Production	8.2	7.4	5.7
Electric Power Systems (SF ₆)	4.7	4.9	5.1
Magnesium (SF ₆)	1.8	3.1	5.5
Aluminum (PFCs)	2.6	2.8	2.8
Semiconductors (PFCs, HFCs & SF ₆)	3.1	8.7	17.5
ODS Substitutes	18.2	34.9	47.6
TOTAL	38.7	61.8	84.2

Notes:

Forecast assumes a "business-as-usual" scenario under which no further industry action occurs.

The emissions forecast includes only direct emissions. Indirect emissions—those that result from changes in energy efficiency after a reduction option has been implemented—are not included. A more detailed discussion of indirect emissions appears in the Life Cycle Climate Performance section.

Voluntary Program Reductions

Under the Climate Change Action Plan, voluntary programs are aimed at achieving cost-effective emission reductions by overcoming various informational, regulatory, financial, and institutional barriers. CCAP was initiated in 1993 and incorporates over forty voluntary industry-government cooperative programs to reduce greenhouse gas emissions. For this analysis, five voluntary programs are considered, all of which target reductions of high GWP gas emissions. The Voluntary Aluminum Industrial Partnership promotes reductions of PFCs from primary aluminum production processes. Similarly, the partnership with HCFC-22 producers commits manufacturers to voluntarily reduce HFC-23 emissions. The remaining three programs are aimed at reducing emissions of PFCs and HFCs from semiconductor production, SF₆ in electrical transmission and distribution systems, and SF₆ in magnesium casting.

Aggregate targets for reducing high GWP gas emissions under CCAP programs include the following: reducing emissions by 13.7 MMTCE by the year 2000 and by 17.4 MMTCE by 2010 (DOS, 1997). Anticipated CCAP emission reductions are not included in the baseline emissions presented in this analysis for the years 2000 through 2010.

In addition to voluntary CCAP programs, Section 612 of the Clean Air Act (CAA) authorized EPA to establish the Significant New Alternatives Policy (SNAP) program. SNAP lists acceptable and unacceptable substitutes for Class I ODS (CFCs, halons, carbon tetrachloride, methyl chloroform, methyl bromide, and hydrobromofluorocarbons (HBFCs)) and Class II ODS (HCFCs). Actions from SNAP are expected to result in emission reductions of approximately 43 MMTCE in 2010. Because these emission reductions are required by regulations promulgated under the CAA, baseline emissions of ODS substitutes already include these reductions.

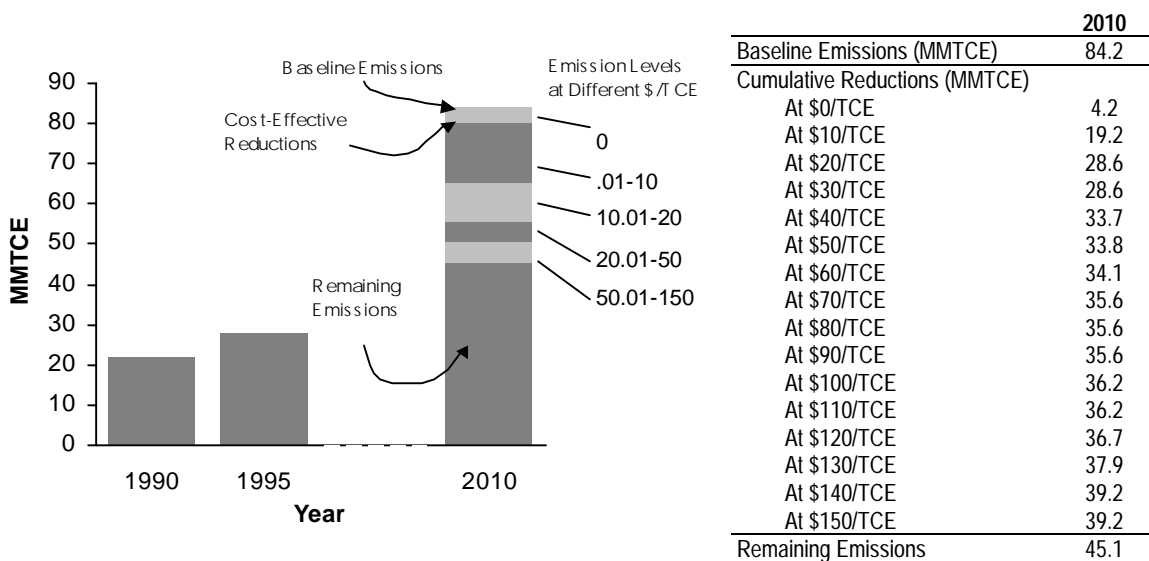
1.4 Economic Analysis of Options for Reducing Emissions of High GWP Gases

Options for reducing emissions of high GWP gases are described in the following chapters for each major source. Where possible, the options are described in terms of the cost of implementation and the reduced emissions that can be achieved. As discussed, costs and emission reductions for options already required by law or expected due to voluntary partnership programs are not included under the baseline. The reduction options assessed in this report were identified from various reports and literature on emission reductions, industry publications, and industry contacts. To date, the most promising options to reduce high GWP gas emissions include:

- implementing new industrial processes that reduce emissions and improve efficiency,
- implementing better housekeeping practices to reduce leaks of high GWP gases,
- installing new, more efficient equipment with lower emission rates, and
- substituting other gases for high GWP gases in a variety of applications, where safety and performance requirements can be met.

This report uses discounted cash flow analysis to estimate the cost of achieving reductions for each technology or practice for each emission source. Costs are presented in dollars per metric ton of carbon equivalent (\$/TCE). Discounted cash flow analysis reflects the decision-making process that manufacturers use when considering investments in emission reduction practices. This approach is the same method EPA has used in developing MACs for methane emissions (see EPA, 1999).

Exhibit 1.5: U.S. Historical and Baseline Emissions and Potential Reductions (at a 4% discount rate)



The costs of reducing emissions have been delineated as both capital investment and operating and maintenance (O&M) costs. In most cases, data on these costs were available; where data were not available, EPA has summarized the options qualitatively.

The benefits calculations incorporate two elements of value. The first element is the value of the savings that are achieved by reducing emissions of a product or by improving process efficiency. For example,

where SF₆ emissions can be reduced by substituting other less expensive gases, the difference in the price of SF₆ and the substitute is counted as a benefit. Where SF₆ emissions are reduced through process improvements, the benefit is the avoided cost of replacing the SF₆ that would have been emitted. In some cases, benefits occur with process efficiencies that lower other O&M costs. The second element of value is the implied value of carbon. This is incorporated in the following way: the discounted cash flow analysis solves for the value of benefits necessary to equal the costs of undertaking the investment. Stated in another way, the analysis solves for the level of benefits needed to yield a net present value (NPV) of zero for the stream of benefits minus costs. Where the level of benefit necessary is in excess of the O&M savings discussed above, the increment needed to yield an NPV of zero is deemed to be the price of carbon. For some options, the price of carbon can be zero or even negative. For most options, however, some value of carbon must be added in order to make the investment economically viable. In this analysis, only options that cost less than \$200 per metric ton of carbon equivalent are included in the MAC.

Discounting

Benefits and costs are discounted over the planning horizon. EPA has used two discount rates. A four percent rate is used for comparison with similar studies by other countries. An eight percent discount rate is also used to more closely approximate private decision-making and for comparison with EPA's MAC for methane emissions (EPA, 1999). All costs and benefits are presented in real year 2000 dollars for emission reductions undertaken in the year 2010.

There is a substantial volume of economic literature about the appropriate discount rate to use in discounting public and private sector benefits and costs over time. The U.S. Office of Management and Budget (OMB) issued guidelines on this topic that suggest using "the opportunity cost of capital, as measured by the before-tax rate of return to incremental private investment" (e.g., about seven percent) (OMB, 2000). In addition, OMB encourages sensitivity analyses using the "social rate of time preference," for which many analysts use the average rate on long-term treasury bonds (about three percent in recent years). Thus, the four and eight percent discount rates used in this analysis are slightly higher and thus more conservative than those suggested in the OMB guidelines.

Life Cycle Climate Performance

The analyses in this report incorporate the "life cycle climate performance" (LCCP) of emission reduction options. The concept of LCCP is based on the fact that replacing high GWP gases in some applications may lead to greater emissions of GHGs elsewhere in the economy. The net effect of some actions to lower high GWP gas emissions, therefore, could increase emissions overall, or at least reduce the net benefits. For example, substitutions for high GWP gases in various refrigeration or air-conditioning systems or insulating foam manufacturing could, in some cases, result in less efficient performance and higher energy use. This in turn would lead to greater energy consumption and higher CO₂ emissions from electricity generation. In some cases, the increased energy consumption outweighs the emission reduction that would be expected by replacing a high GWP gas with one that has no or very low GWP. In other cases, however, the LCCP is improved, such as when alternatives to ODS substitutes are both more efficient and have lower GWPs. Evaluating the LCCP of an option, therefore, involves considering the net of the direct (reduction of high GWP gas) and indirect effects (increase of other greenhouse gases) of that option. Where possible, the LCCP analysis also incorporates losses incurred during the manufacture of the chemical and ultimate disposal of equipment.

This issue is most apparent when evaluating reductions of the high GWP ODS substitutes in the refrigeration and air-conditioning sector and in foams manufacturing. Within the chapters that describe these sectors, the LCCP of each option has been incorporated into the option analyses, where possible. As described in the chapters, LCCP has been incorporated into the analysis by including the additional

costs for greater electricity consumption and reduced benefits that reflect the net of direct and indirect emission effects. It should be noted that some components of the LCCP analysis—such as energy costs and variability in emissions (CO₂) per kilowatt-hour—do vary across the residential, commercial, and industrial sectors. To be conservative, the residential energy cost of \$0.06 per kilowatt-hour and an average emission rate of 0.64 kg CO₂/kWh (EIA, 2000) were chosen for the purpose of this analysis. It also should be noted that while the economic analysis of reduction options in these chapters does take LCCP into account, emission forecasts such as those that appear in Exhibit 1.4 do not include indirect emissions.

While the cost analysis focuses on direct and some indirect costs, it does not incorporate indirect societal benefits associated with reducing emissions of greenhouse gases. In particular, it does not attempt to quantify the avoided costs of mitigating potential damages associated with the effects of increased emissions and concentrations of greenhouse gases (for more information on these potential damages, see Pearce *et al.*, 1996). This is consistent with EPA's analysis of options and costs of reducing methane emissions and with the general approach to consider costs and benefits from the standpoint of the decision-makers implementing emission reduction actions.

1.5 Marginal Abatement Curve

The high GWP gas MAC is shown in Exhibits 1.6 and 1.7 at four and eight percent discount rates, respectively. Each of these two curves uses the appropriate schedule of emission reductions and costs for all of the high GWP gases as presented in Exhibits 1.8 and 1.9. The MAC illustrates emission reductions achievable at increasing values of carbon (\$/TCE).

The MAC is derived by rank ordering individual reduction opportunities by cost per emission reduction amount. Any point along a MAC represents the marginal cost of abating an additional amount of high GWP gas. Any emission reduction corresponding to a zero or negative \$/TCE value illustrates a dual price-signal market, where the savings in high GWP gas (i.e., from not having to replace for emitted gas volumes, or from process improvements that lower production costs while also reducing emissions) pay for the emission reduction effort alone.² Positive values represent the price of carbon equivalent that an emitter would have to receive in addition to any other savings in order to make the emission reductions cost-effective.

The high GWP gas MAC in Exhibit 1.6 illustrates three key findings. First, substantial emission reductions, 4.2 million metric tons of carbon equivalent (MMTCE), are likely to be cost-effective in the absence of a carbon value (i.e., at \$0/TCE). Second, achievable reductions at carbon values of \$20/TCE and \$100/TCE are estimated at 28.6 MMTCE and 36.2 MMTCE, respectively. Third, above \$40/TCE, the MAC becomes relatively inelastic, that is, largely non-responsive to increasing carbon values. This result is expected, given that the analysis does not incorporate new technology innovations that might arise with greater carbon values, increased research and development (R&D) expenditures, or other unexpected technology advances. In sum, the analysis suggests that over 5 percent of baseline emissions could be reduced through cost-neutral or possibly even cost-beneficial changes, and that viable options exist to reduce baseline emissions by nearly one half.

² These improvements, in many cases, have not yet been made due to various institutional barriers and informational asymmetries that might prevent their implementation.

1.6 Uncertainties and Limitations

The major uncertainties in the analysis stem from those inherent in data projection as well as from the lack of published information on reduction options and their costs. Specific examples of areas of uncertainty include the following.

- The projected emission estimates are tied to factors such as growth in usage and demand for specific products or gases—difficult items to project for many sectors. This also introduces a degree of uncertainty about the emission estimates.
- There is significant uncertainty in the levels of future energy prices and the indirect effects of potential emission reduction options. Simplifying assumptions regarding future energy prices were made in order to incorporate LCCP into the appropriate sector analyses, most notably the refrigeration, air-conditioning, and foams sectors.
- Several options that were included in the MAC analysis might become more or less efficient in the future as a result of technological breakthroughs and other innovations. It is important to note that some of those options currently not considered viable may become so in the future.
- Some of the emission reduction options discussed involve using chemicals (as substitutes) that can potentially impact human health and/or safety. Although some technically feasible options were omitted for this reason, some options that remain may still prove not to be feasible upon further research because of health and/or safety concerns.

The lack of specific information on reduction opportunities in many sectors can be attributed to several factors, including the following.

- For some applications, minimal research has been performed on how to limit emissions of ODS substitutes, including developing alternatives for them. This is particularly true for foams, aerosols, fire extinguishers, and solvents.
- Data on both emissions and reduction costs may be highly proprietary for many industrial processes. This is especially true of PFC emissions from semiconductor manufacturing and aluminum smelting.
- For many mitigation options, accurate measures of potential emission reductions or costs are not available. These options, although they are qualitatively discussed in the relevant chapters, are not included in the MAC analysis.

Exhibit 1.6: Marginal Abatement Curve for U.S. High GWP Gas Emissions in 2010 (at a 4% discount rate)

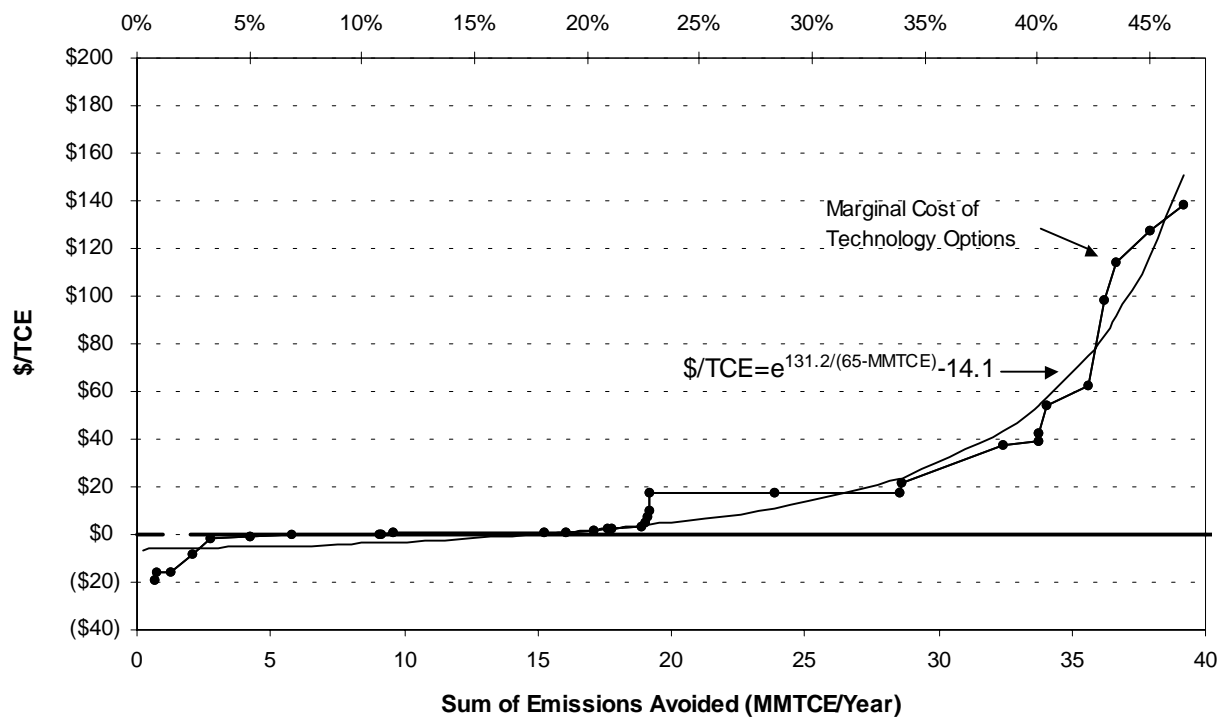


Exhibit 1.7: Marginal Abatement Curve for U.S. High GWP Gas Emissions in 2010 (at an 8% discount rate)

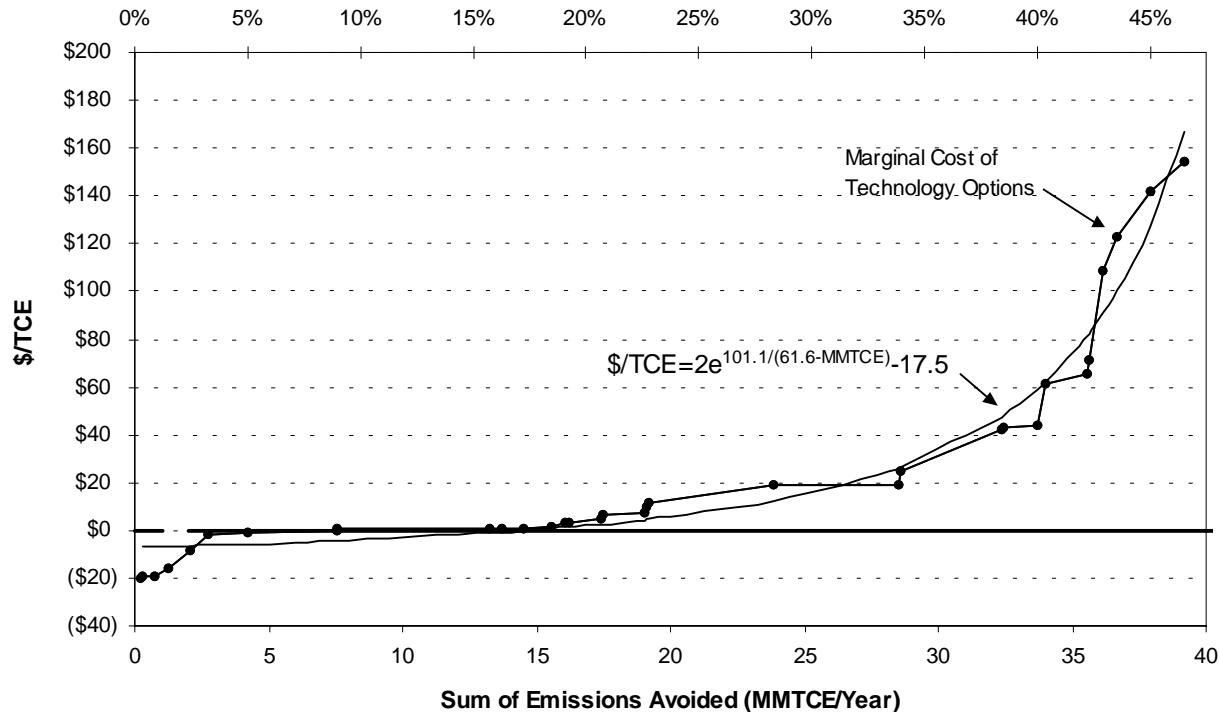


Exhibit 1.8: Composite Marginal Discount Curve Schedule of Options for 2010 (at a 4% discount rate)

#	Source	Activity	Cost (\$/TCE)	Emission Reduction (MMTCE)	Sum of Reduction (MMTCE)	Percent Reduction from 2010 Baseline
1	Aerosols	Hydrocarbon Aerosol Propellants	\$ (20.35)	0.2	0.2	0%
2	Aerosols	Not-in-kind Alternatives	\$ (19.15)	0.5	0.7	1%
3	Fire Extinguishing	Water Mist	\$ (16.19)	<0.05	0.7	1%
4	Foams	PU Spray Foams - Replace HFC-245fa/ CO ₂ (water) with hydrocarbons	\$ (15.70)	0.5	1.2	1%
5	Aerosols	Switching to HFC-152a	\$ (8.14)	0.8	2.1	2%
6	Magnesium Smelting	Good Housekeeping	\$ (1.91)	0.7	2.8	3%
7	Magnesium Smelting	SF ₆ Capture/Recycling	\$ (0.90)	1.5	4.2	5%
8	Refrigeration/AC	Replace DX with Distributed System	\$ 0.02	1.5	5.8	7%
9	Magnesium Smelting	SO ₂ Replacement	\$ 0.25	3.3	9.1	11%
10	Aluminum Smelting	Retrofit-Minor: VSS	\$ 0.27	<0.05	9.1	11%
11	Aluminum Smelting	Retrofit-Major: SWPB	\$ 0.43	0.4	9.6	11%
12	HCFC-22 Production	Thermal Oxidation	\$ 0.64	5.7	15.3	18%
13	Solvents	Alternative Solvents	\$ 0.88	0.8	16.1	19%
14	Electric Utilities	Leak Detection and Repair	\$ 1.62	1.0	17.1	20%
15	Electric Utilities	Recycling Equipment	\$ 2.30	0.5	17.6	21%
16	Aluminum Smelting	Retrofit-Major: CWPB	\$ 2.50	0.2	17.8	21%
17	Refrigeration/AC	Leak Reduction Options	\$ 3.58	1.2	18.9	22%
18	Aluminum Smelting	Retrofit-Major: HSS	\$ 5.23	0.1	19.1	23%
19	Aluminum Smelting	Retrofit-Major: VSS	\$ 7.25	0.1	19.1	23%
20	Solvents	NIK Semi-Aqueous	\$ 9.63	<0.05	19.2	23%
21	Foams	PU Appliance Foams - Replace HFC-134a with cyclopentane	\$ 17.18	<0.05	19.2	23%
22	Semiconductor Manufacturing	NF ₃ Drop-In	\$ 17.51	4.7	23.9	28%
23	Semiconductor Manufacturing	NF ₃ Remote Cleaning	\$ 17.51	4.7	28.6	34%
24	Solvents	NIK Aqueous	\$ 21.57	<0.05	28.6	34%
25	Semiconductor Manufacturing	Plasma Abatement	\$ 37.87	3.8	32.4	38%
26	Semiconductor Manufacturing	Capture/Recycling	\$ 39.58	1.3	33.7	40%
27	Solvents	Retrofit Options	\$ 42.45	<0.05	33.8	40%
28	Fire Extinguishing	Inert Gas Systems	\$ 53.86	0.3	34.1	40%
29	Refrigeration/AC	HFC Secondary Loop Systems	\$ 62.57	1.5	35.6	42%
30	Refrigeration/AC	Ammonia Secondary Loop Systems	\$ 98.61	0.6	36.2	43%
31	Foams	PU Spray Foams - Replace HFC-245fa/ CO ₂ (water) with CO ₂ (water)	\$ 114.09	0.5	36.7	44%
32	Semiconductor Manufacturing	Catalytic Destruction	\$ 127.29	1.2	37.9	45%
33	Semiconductor Manufacturing	Thermal Destruction	\$ 138.61	1.3	39.2	46%

Exhibit 1.9: Composite Marginal Discount Curve Schedule of Options for 2010 (at an 8% discount rate)

#	Source	Activity	Cost (\$/TCE)	Emission Reduction (MMTCE)	Sum of Reduction (MMTCE)	Percent Reduction from 2010 Baseline
1	Aerosols	Hydrocarbon Aerosol Propellants	\$ (20.32)	0.2	0.2	0%
2	Fire Extinguishing	Water Mist	\$ (19.42)	<0.05	0.3	0%
3	Aerosols	Not-in-kind Alternatives	\$ (19.12)	0.5	0.7	1%
4	Foams	PU Spray Foams - Replace HFC-245fa/ CO ₂ (water) with hydrocarbons	\$ (15.64)	0.5	1.2	1%
5	Aerosols	Switching to HFC-152a	\$ (8.09)	0.8	2.1	2%
6	Magnesium Smelting	Good Housekeeping	\$ (1.91)	0.7	2.8	3%
7	Magnesium Smelting	SF ₆ Capture/Recycling	\$ (0.89)	1.5	4.2	5%
8	Magnesium Smelting	SO ₂ Replacement	\$ 0.24	3.3	7.5	9%
9	Aluminum Smelting	Retrofit-Minor: VSS	\$ 0.54	<0.05	7.6	9%
10	HCFC-22 Production	Thermal Oxidation	\$ 0.73	5.7	13.3	16%
11	Aluminum Smelting	Retrofit-Major: SWPB	\$ 0.77	0.4	13.7	16%
12	Solvents	Alternative Solvents	\$ 0.88	0.8	14.5	17%
13	Electric Utilities	Leak Detection and Repair	\$ 1.62	1.0	15.5	18%
14	Electric Utilities	Recycling Equipment	\$ 3.28	0.5	16.1	19%
15	Aluminum Smelting	Retrofit-Major: CWPB	\$ 3.30	0.2	16.2	19%
16	Refrigeration/AC	Leak Reduction Options	\$ 5.08	1.2	17.4	21%
17	Aluminum Smelting	Retrofit-Major: HSS	\$ 6.82	0.1	17.5	21%
18	Refrigeration/AC	Replace DX with Distributed System	\$ 7.21	1.5	19.1	23%
19	Aluminum Smelting	Retrofit-Major: VSS	\$ 9.58	0.1	19.1	23%
20	Solvents	NIK Semi-Aqueous	\$ 11.55	<0.05	19.2	23%
21	Semiconductor Manufacturing	NF ₃ Drop-In	\$ 18.57	4.7	23.9	28%
22	Semiconductor Manufacturing	NF ₃ Remote Cleaning	\$ 18.57	4.7	28.6	34%
23	Solvents	NIK Aqueous	\$ 25.02	<0.05	28.6	34%
24	Semiconductor Manufacturing	Plasma Abatement	\$ 41.95	3.8	32.4	38%
25	Foams	PU Appliance Foams - Replace HFC-134a with cyclopentane	\$ 43.25	<0.05	32.4	38%
26	Semiconductor Manufacturing	Capture/Recycling	\$ 43.99	1.3	33.7	40%
27	Fire Extinguishing	Inert Gas Systems	\$ 61.44	0.3	34.0	40%
28	Refrigeration/AC	HFC Secondary Loop Systems	\$ 65.30	1.5	35.6	42%
29	Solvents	Retrofit Options	\$ 71.24	<0.05	35.6	42%
30	Refrigeration/AC	Ammonia Secondary Loop Systems	\$ 108.67	0.6	36.2	43%
31	Foams	PU Spray Foams - Replace HFC-245fa/ CO ₂ (water) with CO ₂ (water)	\$ 122.52	0.5	36.7	44%
32	Semiconductor Manufacturing	Catalytic Destruction	\$ 141.93	1.2	37.9	45%
33	Semiconductor Manufacturing	Thermal Destruction	\$ 154.54	1.3	39.2	46%

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